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13. ABSTRACT

The effects of increased ambient air pressures on standing steadiness at 2.2 ATA, 4 ATA, 7 ATA and 19 ATA, as compared with results obtained in two control situations at ambient air pressure 1 ATA, were studied in 10 experienced divers. Body sway was recorded quantitatively by statometry and in four different conditions: with open and closed eyes and in sagittal and lateral directions. The device used-Statometer IV-allowed analog and digital recording and evaluation of variations in frequency and amplitude of the pattern of body sway, and an advanced statistical analysis was made by using a randomized block factorial analysis of variance design. The results indicated that (1) there is a strong quadratic relationship between balance and depth, (2) deterioration in balance increases at a much faster rate for the eyes closed condition than for the eyes open condition as depth is increased, (3) there are highly significant individual differences, (4) the performance at depth is related to the performance at the surface, (5) there seems to be no habituation or other adaptation to the test device and (6) there seem to be no essential after-effects to the exposure to increased ambient air pressure under the present conditions. It was concluded that the postural disturbances at increased ambient air pressure might be related to the effect of the breathing medium on the central nervous system as one symptom of nitrogen narcosis in man.

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EFFECTS OF INCREASED AMBIENT AIR PRESSURE ON STANDING STEADINESS IN MAN

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Effects of Increased Ambient Air Pressures on Standing Steadiness in Man

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The effects of increased ambient air pressures on standing steadiness at 2.2 ATA, 4 ATA, 7 ATA and 10 ATA, as compared with results obtained in two control situations at ambient air pressure (1 ATA), were studied in 10 experienced divers. Body sway was recorded quantitatively by statometry and in four different conditions: with open and closed eyes and in sagittal and lateral directions. The device used—Statometer IV—allowed analog and digital recording and evaluation of variations in frequency and amplitude of the pattern of body sway, and an advanced statistical analysis was made by using a randomized block factorial analysis of variance design. The results indicated that (1) there is a strong quadratic relationship between balance and depth, (2) deterioration in balance increases at a much faster rate for the eyes closed condition than for the eyes open condition as depth is increased, (3) there are highly significant individual differences, (4) the performance at depth is related to the performance at the surface, (5) there seems to be no habituation or other adaptation to the test device and (6) there seem to be no essential aftereffects to the exposure to increased ambient air pressure under the present conditions. It was concluded that the postural disturbances at increased ambient air pressure might be related to the effect of the breathing medium on the central nervous system as one symptom of nitrogen narcosis in man.

BODY SWAY MOTION represents the critical mode in control of body posture because of the inherent unstable "inverted pendulum" characteristics of the body. Sensors in all areas of the organism are used in the control of posture. The sensors obtain information concerning position, orientation and posture from both internal and external sources.

In the central nervous system the task of sensory processing and generation of muscle commands is multilevel, the lowest level of coordination located at the spinal ventral roots and subsequent levels extending upward to the highest brain centers.[10,17]

Nashner[17] has treated the basic functional properties of the posture control system as a multiloop system in which a number of specialized feedback sensors contribute to the generation of commands. Proprioceptive sensors and neural processing at the lowest levels enable crude but fast acting responses based on information from body centered frames. "Inertial" sensors and higher center processing provide more accurate, adaptable control but with longer processing delays. Hence, postural control is a highly nonstationary process in which responses to transient disturbances are initiated at the lowest levels. Allocation of control then "radiates" towards to the higher centers where successive corrections, based on more complete information, fine tune the initial response.

It has been found that during quiet standing on a rigid flat surface the ankle stretch reflex gain is about one-third that necessary for postural stability.[17] Small "stiction" forces acting between fibers within both intra- and extra-fusal muscles, however, supplement this reflex gain, and together they provide a gain adequate for complete stability for very small ankle deflections. The kinesthetic cues, associated with changes in pressure distribution of the feet, are the first signals of postural divergence. These signals trigger a multiplicative increase in the reflex loop gain proportional to the disturbance amplitude. Because deep pressure sensation habituates, an additional sense, either visual or utricular otolith information, is necessary to provide drift stabilization.[17]

It is well established that various drugs especially alcohol, can disturb the coordination, and certain gases and gas mixtures have similar effects.[8,11,12,13] Subjective feelings of dizziness and vertigo during exposure to increased ambient air pressure were reported repeatedly by divers acting as subjects in psycho-physiological experiments at Karolinska Institutet and at the Naval Diving Training Center in Stockholm, Sweden.[1,2,6] These symptoms were also noted after inhalation of various gas mixtures, including helium-oxygen at increased atmospheric pressures.

Preliminary results from an earlier study[3] showed that

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The statistical analysis has been done in part at the U.S. Navy Experimental Diving Unit, Washington, D.C.

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body sway, measured by means of a so called Statometer, increased during exposure to 10 ATA in the same proportion in sagittal direction, lateral direction eyes open and eyes closed. The mean scores increased by 95% on the average and the differences were highly statistically significant. The variability also increased significantly at 10 ATA.

It seemed likely, then, as a working hypothesis, to relate the serious postural disturbances at 10 ATA to a narcotic effect of the breathing medium as one symptom of inert gas narcosis in man at raised ambient air pressure, acting upon the central nervous system. No training effects were found, nor any significant after-effects of the exposure to 10 ATA.

In the experiment reported in this paper an attempt was made to observe a possible relationship between graded increases in ambient air pressure and changes in body sway under various conditions: with open and closed eyes and in sagittal and lateral directions while breathing air.

METHODS

Subjects and Compression-decompression Procedure—The same 10 experienced test divers from the Royal Swedish Navy who acted as subjects in the earlier investigation[3] were exposed to ambient air pressures of 2.2 ATA, 4 ATA and 7 ATA in a dry compression chamber after two control sessions at 1 ATA. The order of the experiments was rotated so that 5 subjects started the testing at 2.2 ATA and 5 subjects started at 7 ATA. After a 50-minute exposure to maximum 7 ATA, decompression took a total of 161 minutes, whereupon a post-control experiment was performed at 1 ATA. The original test data from the earlier exposure to 10 ATA were used in the evaluation of the results.

Instrumentation—The Statometer Model IV, developed by the Working Group on Statometry at the Department of Alcohol Research, Karolinska Institutet, Stockholm, Sweden,[7] was used to record and evaluate changes in body posture or body sway (standing steadiness). The apparatus comprises basically three main units: for data acquisition, for recording and storage and for evaluation and data analysis.

In the system for signal uptake (data acquisition), the Posture Sensor Transducer Unit, the movements of the subject standing on the Posture Unit are transformed into a varying voltage. The output signals representing both lateral (x) and sagittal (y) movements, are calibrated in kpcm force displacement or in Statometer Units (score), showing a linear proportionality to the force applied to the plate.

For recording, the outgoing signals are stored on line on magnetic tape and are monitored on an analog inkwriter.

For quantitative evaluation the signals are fed into an A/C converter, where the varying voltage from the signal units is converted into discrete pulses which are counted electronically during one-sec periods, corresponding to the area under the curve.

The magnetic type recordings are used for visual pattern recognition and identification of the numerical data and for analysis of wave patterns and frequency distribution.

Besides pattern evaluation three main parameters were computed: mean score ± S.E., based on 50 counts at each recording, intra-individual and inter-individual variability.

Experimental Design—The recordings were taken with the subject in the compression chamber standing on the posture sensor transducer unit of the Statometer in a Romberg position with feet together, eyes open or closed. The variations in standing steadiness were recorded on magnetic tape and monitored on an inkwriter, the tape recorder and the inkwriter being placed outside the chamber. The tape recordings were then processed at the Department of Alcohol Research, Karolinska Institutet.

The standard procedure which was followed during a test was comprised of:

Training	60 secs
1st recording—eyes open	70 secs
Interval	30 secs

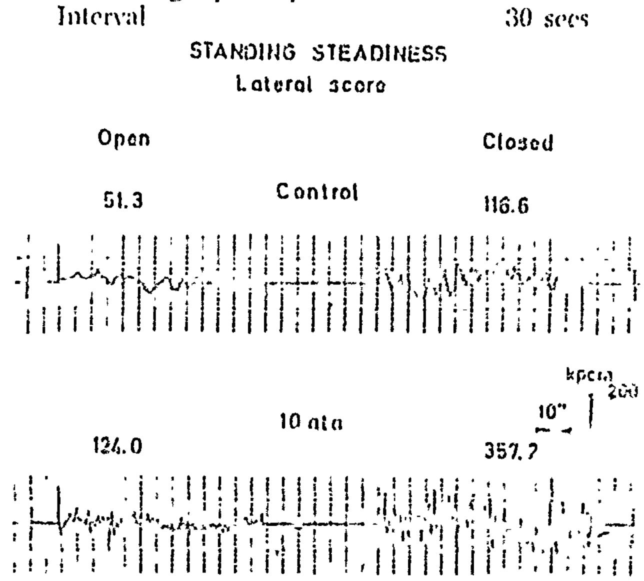

Fig. 1. Actual recordings of standing steadiness (body sway), open (left) and closed eyes (right), lateral direction.

Air pressure	Open eyes: Fluctuations Freq. p s	Open eyes: Fluctuations Ampl. kpcm	Open eyes: Mean score ± S.E. (N = 50)	Closed eyes: Fluctuations Freq. p s	Closed eyes: Fluctuations Ampl. kpcm	Closed eyes: Mean score ± S.E. (N = 50)
1 ATA	0.21	30-100	51.3 ± 4.0	0.[illegible]3	60-200	116.0 ± 9.1
10 ATA	0.48	50-150	1[illegible] ± 10.3	0.63	75-300	35[illegible] ± 32.1
Diff. (10-1 ATA)	↑109%		↑11[illegible]% (p<0.001)	↑106%		↑206% (p<0.001)

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1st recording—eyes closed	70 secs
Interval	30 secs
2nd recording—eyes open	70 secs
Interval	30 secs
2nd recording—eyes closed	70 secs

During one test day six subtests were run: (1) precontrol 1 ATA; (2) control 1 ATA (after an interval of 20 minutes); (3) hyperbaric test pressure level 1 (after 5 minutes at pressure level); (4) hyperbaric test pressure level 2 (after 5 minutes at pressure level); (5) hyperbaric test pressure level 3 (after 5 minutes at pressure level); (6) post-control 1 ATA (after a decompression period of 161 minutes).

RESULTS

An example of the recordings made at 1 ATA and 10 ATA is given in Figure 1. The increase in amplitude as well as frequency of sway and variability with time with increase in ambient air pressure is noticed as well as the

STANDING STEADINESS (BODY SWAY)

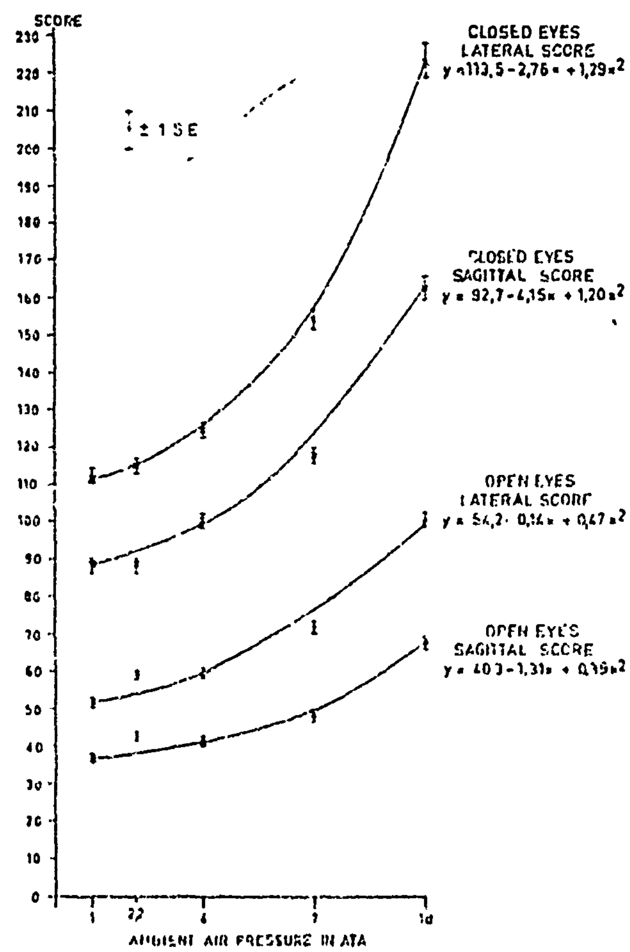

Fig. 2. Relation between standing steadiness (body sway) in Statometer Units (score) and pressure level (depth). Means of 10 experienced divers while breathing air. Curves are best fit curves significant at the $p < 0.001$ level, implying a quadratic relationship.

increase when eyes were closed. The pattern of sway varied from subject to subject; large slow deviations away from the main position, as well as small and rapid excursions around the main position were found.

The effects of graded increases in ambient air pressure are given in Figure 2. Already at 2.2 ATA in two conditions with open eyes the increase from the control (1 ATA) was statistically significant ($p < 0.05$). All effects at higher pressures were highly statistically significant ($p < 0.001$).

For further evaluation of the present data a randomized block factorial analysis of variance design was used. The overall results are presented in Table I. Blocking across subjects was incorporated to remove individual differences from the error term. The subjects were tested twice with their eyes open and twice with their eyes closed (*Factor A*). Each subject was tested four times at each of five pressure levels (*Factor B*). Shifts in balance force were measured in two planes: lateral and sagittal (*Factor C*).

The results indicate that the individual differences on the balance test (*Blocks*) are statistically significant at the $p < 0.001$ level. In other words, a difference as large as the one obtained could be expected by chance in less than one of a thousand replications of this experiment.

The differences noted between the eyes open and eyes closed condition (*Factor A*) are also statistically significant at the $p < 0.001$ level, which is also the fact for the differences between the pressure levels (*Factor B*).

When the treatment levels for a given factor form a series of steps along an ordered scale, i.e., increasing dosage, intensity, pressure, time, etc. then treatment variation can be subdivided into linear, quadratic, cubic, etc. trend components. A trend analysis of Factor B (depth, pressure) indicates that when subjects are breathing air there is an overall quadratic relationship between balance and depth. This is illustrated in Figure 2.

The interaction between *Factor A* (eyes open or closed) and *Factor B* (depth) is statistically significant at the $p < 0.001$ level.

Also, the direction of movement (*Factor C*) is statistically significant ($p < 0.001$). Without exception the subjects displayed more lateral than sagittal movement.

The results obtained in the pre-control and post-control situations at 1 ATA were compared by means of the t-test. No statistically significant differences ($p > 0.05$) were found, which is quite in accordance with the earlier findings.[3] Finally, the results, shown in Table II, indicate that performance at depth is related to performance on the surface. In other words, those people who perform well on the surface also perform well at depth.

As mentioned above the subjects were tested twice with open eyes and twice with closed eyes at each pressure level. The test-retest reliability for each two sets of tests was high and stable for all variables studied in this investigation and, therefore, it was possible to use each pair of measurements as one set in the final analysis. The test-retest reliability is given in Table III.

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DISCUSSION

The idea to use statometry as a quantitative physiological measurement of inert gas narcosis in man is not new. In 1942 Berggren[6] started a pilot study to record effects of increased ambient air pressure on the central nervous system by employing a series of psychomotor tests including methods for quantitative photographic recording of changes in body sway. This procedure was originally developed for studying effects of alcohol and drugs.[11] Unfortunately, the experiments on divers were discontinued due to Berggren's untimely death.

More recently reports on subjective feelings of dizziness and vertigo during exposure to increased ambient air pressure[1,2,5] and episodes of imbalance have actualized this investigation. While balance disturbances occur during exposure to increased ambient air pressure the reported episodes of so-called alternobaric vertigo[16,18] seem to occur either during or immediately after ascent. This suggests that overpressurization of the middle ear may be more important than a negative pressure in the middle ear.[18] Most likely the vertigo thus seems to be induced by pressure changes in the middle ear rather than to a narcotic effect of the breathing medium upon the central nervous system.

As one step in an attempt to localize possible sites and mechanisms of action underlying the observed balance disturbances in divers underwater, the possible influences of hyperbaric conditions (10 ATA) on certain vestibular reactions were studied.[4] No changes in the reaction pattern of the vestibular-ocular reflex are to graded movements of the head nor to acceleration and retardation during rotation were found. Neither were there any differences observed in the activity between the left and right labyrinths during exposure to an ambient air pressure of 10 ATA. The results showed that certain pathways of the vestibular system were not perturbed by high ambient air pressures, but the results from the present investigation, on the other hand, show that other systems under vestibular control, e.g., the postural system, are clearly implicated. However, this is in strong need of further investigation.

Perhaps one of the most interesting findings in the analysis of the results of the present investigation is the interaction between the visual conditions (open/closed eyes) and the depth conditions (*Factor AB* in Table I). The results indicate that deterioration in balance increases at a much faster rate for the eyes closed condition than for the eyes open condition as depth is increased. It appears that balance is deteriorating, but that the subjects are able to compensate for this deterioration as long as they have their eyes open and a visual reference is present. This seems to be a reasonable explanation since most of man's spatial orientation information comes via vision and that body sway is reduced to half with open eyes as compared to eyes closed.[8,9]

In diving to deep depths or in turbid or amorphous water the visual reference is lost along with many of the other orientation cues. The decreased visibility as well as the reduced illumination occurring during a dive reduce the effect of visual cues and impair standing steadiness and hence add to the impairing effect of exposure to increased ambient air pressure. The combined effect of 10 ATA and eliminated visual cues as compared to the sco[illegible] with open eyes at 1 ATA, caused the body sway with closed eyes at 10 ATA to increase to an average of 453% of the normal (1 ATA) with open eyes.[3]

Under these conditions it seems reasonable to suspect that man will have a great deal of trouble with orientation under water. The vestibular system is as sensitive to gravity under water as in air, but postural cues for a free-floating diver are very much reduced because of his neutral buoyancy. When these losses of sensory information are coupled with man's decreased a[illegible] to process information while breathing high p[illegible] air[1,2,5] it is not difficult to understand the reports of people swimming down instead of up during open sea deep air Scuba dives. If, then, an episode of alternobaric vertigo occurs in addition to the balance disturbances induced by the narcotic effect of the breathing medium, the actual dive may be catastrophic to the diver.

TABLE I. RANDOMIZED BLOCK FACTORIAL ANALYSIS OF VARIANCE OF CHANGES IN STANDING STEADINESS (BODY SWAY) IN 10 EXPERIENCED DIVERS (BLOCKS) AT 1, 2.2, 4, 7 AND 10 ATA (DEPTH) WITH OPEN AND CLOSED EYES (EYES) IN THE LATERAL AND SAGITTAL DIRECTIONS (DIRECTION) WHILE BREATHING AIR.

SOURCE	SS	df	MS	F
Blocks	91253	9	10139	18.6***
Treatments				
(A) Eyes	220022	1	220022	419.6***
(B) Depth	108277	4	27069	49.6***
(AB)	13754	4	3939	7.2***
(C) Direction	29773	1	29773	54.5***
(AC)	1007	1	1008	1.8
(BC)	2103	4	526	0.96
(ABC)	176	4	44	0.08
Residual	93328	171	546	
Total	570695	199		

*** $P < 0.001$

TABLE II. CORRELATION BETWEEN BODY SWAY IN THE HYPERBARIC (2.2, 4, 7 AND 10 ATA) AND CONTROL CONDITION (1 ATA) WITH OPEN AND CLOSED EYES IN 10 EXPERIENCED DIVERS WHILE BREATHING AIR.

Eyes Open		Eyes Closed	
Depths	Correlation	Depths	Correlation
1-2.2	0.66	1-2.2	0.79
1-4	0.74	1-4	0.73
1-7	0.61	1-7	0.69
1-10	0.78	1-10	0.69

TABLE III. TEST-RETEST RELIABILITY. CORRELATION BETWEEN BODY SWAY IN FIRST AND SECOND RECORDING AT VARIOUS PRESSURE LEVELS (DEPTH) IN 10 EXPERIENCED DIVERS WHILE BREATHING AIR.

Depth	Lateral Movement		Sagittal Movement	
	Closed Eyes	Open Eyes	Closed Eyes	Open Eyes
1	0.80	0.92	0.83	0.92
2.2	0.83	0.82	0.59	0.68
4	0.50	0.71	0.84	0.91
7	0.93	0.77	0.83	0.85
10	0.67	0.89	0.96	0.75
1	0.74	0.70	0.58	0.57

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The high individual differences found in this investigation indicate that each individual has his own individual body sway pattern, and the correlation between the results obtained on the surface and the results obtained at depths in each individul is high and very stable at all the pressure levels tested, varying from r = .66 to r = .81 for open eyes, and from r = .69 to r = .79 for closed eyes (Table II). That means that performance at depth is related to performance on the surface.

The findings in the earlier investigation[3] that there were no systematic changes from the pre-control to the post-control situation indicated that there were no *essential* after-effects with regard to body sway. This is confirmed in this investigation for three out of the four comparisons possible. The actual t-values are: in the lateral direction closed eyes 1.097, and open eyes 2.098 ($p < 0.05$); in the sagittal direction closed eyes 1.293, and open eyes 1.231.

The findings in this study seem to correspond very well with the results of an investigation on the effects of hypoxia on standing steadiness by Bjerver & Persson (1957).[8] They found that after one minute inhalation of 10% oxygen and 90% nitrogen at normal ambient pressure an increase in statometer values was recorded and increased successively during inhalation of the gas mixture, reading a maximum one-half minute after the cessation of the gas mixture inhalation. They also found a rather large variation between the subjects. Arterial oxygen saturation was followed continuously. Whether or not changes in the carbon dioxide tension in the tissues would cause changes in body sway has not yet been elucidated.

From the results of this investigation it seems likely to confirm the conclusion from the earlier study[3] that the serious postural disturbances at increased ambient air pressures might be related to the effect of the breathing medium as one symptom of nitrogen narcosis in man. This symptom is detectable at an early stage by recording the changes in standing steadiness (statometry). The increased ambient air pressure seems to act upon the central nervous system, affecting a number of integrative processes which are engaged in maintaining equilibrium while standing and also involving ocular pathways other than those so far tested. The mechanism may differ from that of other agents causing postural disturbances, e.g., ethanol, having first dis-inhibiting and then blocking effects on a number of central nervous system structures, for instance the reticular formation.[13,14,15]

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